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14. ABSTRACT
The main topics along which the investigations under the grant were made encompassed the development of basic theory of stochastic electromagnetic fields, their free-space propagation, interaction with various media, and optical systems, their scattering from continuous media and particles, their propagation in turbulent media. In addition, deep analysis of existing and development of new techniques which utilize stochastic beams is carried out. Among our main contributions are the theory of weak scattering of stochastic fields from collections of particles, theory of electromagnetic scattering, combination of theories of propagation in turbulence and weak particle scattering, propagation of stochastic fields in non-classic turbulence and the influence of the power-spectrum slope on the beams, and the active LIDARs using stochastic beams. These results have been published in 51 peer-reviewed papers and presented at 30 conferences and invited talks given by the PI, her collaborators and students. Main collaborations included A. Mahalov (ASU), G. Gbur (UNCC), E. Watson (UD), E. Wolf (UR), F. Gori (Universita Roma Tre, Italy), Y. Cai (Univ. of Suzou, China), E. Shchepakina (Samara State Aerospace University, Russia), Y. Baykal (Cankaya University, Turkey).

15. SUBJECT TERMS
Atmospheric turnulence, Stochastic electromagnetic beams, Particle scattering

FINAL REPORT

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The main topics along which the investigations under the grant were made encompassed the development of basic theory of stochastic electromagnetic fields, their free-space propagation, interaction with various media, and optical systems, their scattering from continuous media and particles, their propagation in turbulent media. In addition, deep analysis of existing and development of new techniques which utilize stochastic beams is carried out. Among our main contributions are the theory of weak scattering of stochastic fields from collections of particles, theory of electromagnetic scattering, combination of theories of propagation in turbulence and weak particle scattering, propagation of stochastic fields in non-classic turbulence and the influence of the power-spectrum slope on the beams, and the active LIDARs using stochastic beams. These results have been published in 51 peer-reviewed papers and presented at 30 conferences and invited talks given by the PI, her collaborators and students. Main collaborations included A. Mahalov (Arizona State Univ., AZ), G. Gbur (Univ. at Charlotte, NC), E. Watson (Univ. of Dayton, OH), E. Wolf (Univ. of Rochester, NY), F. Gori (Universita Roma Tre, Italy), Y. Cai (Univ. of Suzou, China), E. Shchepakina (Samara State Aerospace University, Russia), Y. Baykal (Cankaya University, Turkey).

DESCRIPTION OF PUBLISHED BODY OF WORK

1. Development of theories of stochastic electromagnetic light fields

a) New concepts relating to stochastic fields [2], [28], [40]

Among the major advances in the basic theory of stochastic fields that we have made is the formulation of the *superposition law* of two electromagnetic stochastic beam-like fields [2]. This law allows predicting various statistical properties of the mixture of beam with arbitrary spectral, correlation and polarization properties. We have also introduced the important new quantity the *degree of paraxiality* for scalar [28] and electromagnetic [40] stochastic fields. This degree allows quantifying the discrepancy between a given field and its paraxial counterpart.

b) New types of stochastic fields [18], [22]

We have introduced three-dimensional, scalar, *spherically symmetric, homogeneous sources* [18]. The homogeneity here means that the field correlation on the surface of the sphere, at two points, is only a function of the central angle between these points. We have found three different model sources (which we name Legendre, Gaussian and Spherical) and established their coherent mode representations, i.e.

the structure of eigenfunctions and distribution of eigenvalues. We have also introduced a family of beam-like fields with Laguerre-Gauss intensity profile and Gaussian correlation, called standard and elegant *partially-coherent Laguerre-Gauss beams*, together with derivation of their free-space propagation laws [22].

b) Stochastic fields in free space [12], [15], [51]

Free-space propagation of the recently introduced quantity degree of cross-polarization has been investigated in [12]. It was found that for a typical stochastic beam this quantity can take on any non-negative value on propagation, in difference with the classic degree of coherence. We have also studied the effect of a twist phase of a stochastic electromagnetic source on the polarization properties of the generated beam [15]. The twist phase in the vectorial fields was introduced in that reference for the first time. Conditions for polarization invariance for quasi-homogeneous sources were derived in [51]. Under such restrictions all polarization properties of the far-field are the same as those of the source, independently of the direction.

c) Stochastic fields in various media [24-25], [31-32]

Evolution of typical stochastic fields in negative phase materials, and in stratified media being combinations of positive and negative phase materials was discussed in [24] and [31]. Interaction of stochastic beams with gain and absorptive media belongs to [25]. In [32] we have analyzed the spectral changes in far-fields generated by the Gaussian Schell-model beams and propagated in deterministic media with arbitrary refractive properties.

d) Stochastic fields in various optical systems [1], [3-4], [16-17], [33], [41], [47]

The effect of an apertured, non-symmetrical optical system on statistical properties of electromagnetic random beams was shown via derivation of the cross-spectral density matrix of a typical beam [1]. This study is important for interpretation of experimental results since in practice, as a rule, the beams are modified by auxiliary optical elements, such as expanders. We have dedicated several studies to interaction of the beams of interest with Gaussian optical resonators [3-4], [16], [33] and found out how various beam properties, and, in particular, polarization properties saturate after sufficiently many passages within the cavity, depending on the initial condition and resonator size and stability parameters. An experiment on spectral shifts and switches in focused stochastic beams was performed jointly with group of Prof. Y. Cai (Univ. of Suzou, China) [17], which confirmed the corresponding theoretical predictions, made earlier. A study about two-point correlation properties of typical stochastic beams on passage through the non-image forming optical devices (polarizers, spatial light modulators, and others) was carried out in [41] where cross-polarization and intensity-intensity correlation properties are shown to be drastically influenced by the devices. Imaging of stochastic electromagnetic light by the human crystalline lens (perhaps the most important natural lens) is done in [47] and it is shown how the eye modifies the incident light with various spectral, correlation and polarization features.

e) New techniques using stochastic fields [9], [21], [30]

Among the techniques that can only perform with stochastic fields is the ghost imaging scheme. We have investigated in [9] how a twist phase affects the ghost image visibility. The best visibility is obtained when the source twist phase is zero. In [30] we have introduced the ghost imaging by means of electromagnetic rather than scalar beams and related polarization light with image visibility. Another class of techniques uses radiation force as the means of manipulating of particles, for example, their twisting or trapping. We have found in [21] how the twist phase in stochastic fields influences such experiments.

2. Scattering of stochastic fields

a) scattering from a single particles and collections [6], [13], [43], [50]

We have developed the theory of weak potential scattering of stochastic fields from deterministic and random collections of particles, under the validity of the first Borm approximations [6], [13]. Our main contribution is the formula which relates the correlation properties of the incident field and of the scattering collection with the various properties of the scattered field. A new measure of correlation in particle collection, the *pair-structure factor*, was introduced and modeled. Pair structure factor specifies the change in correlation that the incident field undergoes on interaction with the collection, it depends on two incident and two scattered directions. The collections with different pair-structure factors but the same well known structure factors were shown to modify the light differently. A separate study was dedicated to correlations in intensity of scattered light at one and two directions [43]. This is the extension of the Hunbury-Brown Twiss work to the case of particle scattering. In [50] extension of the pair-structure factor to *pair-structure matrix*, for the case of several types of particles was made. Pair-structure matrix is responsible for taking into account correlations between particles of the same and different types.

b) other [35], [44], [49]

The weak scattering theory was extended from scalar to electromagnetic domain in [35]. This development made it possible to predict how polarization properties of incident waves are modified on scattering, in the most general case, when both the source and the scatterer are of random nature. The formulation is developed for both intermediate and far zone of the scatterer, in the later case only the transverse part of the field is considered, and Fourier relation is used, considerably simplifying numerical calculations. An inverse problem of finding an unknown position of a particle embedded into random collection of other particles is solved via making a set experiments [44]. Scattering of fields from particles with semi-soft boundaries was considered in [49]. The particles with potentials that can adjust hardness has been modeled with the help of the multi-Gaussian functions, i.e. the linear combination of weighted Gaussian functions. We have shown that the hardness of the boundary affects the angular distributions of the scattered field's intensity. This analysis is important for practical applications – real particle potentials can have fuzzy edges.

3. Propagation of fields in the turbulent atmosphere

a) non-classic turbulence [20], [26], [36]

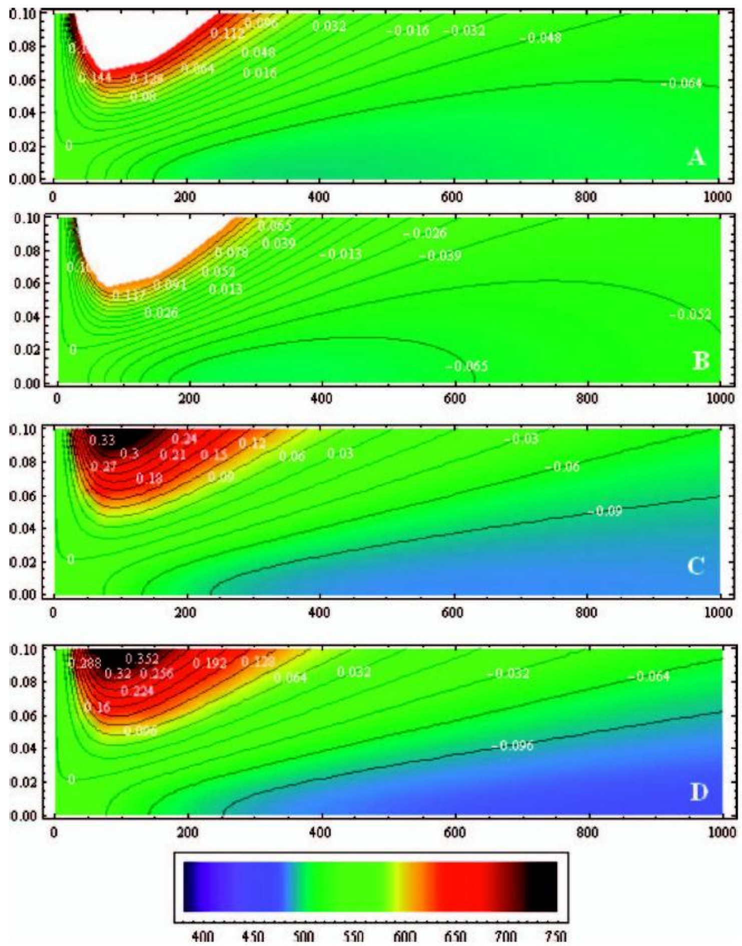

Fig. 1 Density plots of actual spectral shift overlapped with contour plots of normalized spectral shift as a function of z (horizontal axis, in meters) and r (vertical axis, in meters) for (a) α = 3.01, (b) α = 3.10, (c) α =3.67, and (d) α =4.99.

We have made several investigations concerning interaction of optical beams with non-conventional atmospheric turbulence. In [20] we have used real data for the refractive index structure parameter C_n^2 for the Earth's jet stream, at an altitude of 8-12 km, for propagation of a typical Gaussian beam. We have compared our numerical results with theoretical predictions for beam propagation in the absence of the jet screen and established that the jet-stream affects the beam much stronger than the classic well-formed turbulence. The influence of the power-spectrum slope constant α on the stochastic beam properties was investigated in [26] and [36]. It was found that for slope constant, smaller than α = 11/3 ≈ 3.67 (classic, Kolmogorov case) the turbulence affects all the statistics of the beam stronger, the maximum effect is found to be about value 3.11. Turbulence with slope constants smaller than Kolmogorov's is found to occur at altitudes up to 2-8 km. On the other hand, turbulence with slope constants larger than Kolmogorov's is found to be at altitudes 8-20 km, and was shown to affect the optical beams less. In particular the analysis of spectral changes of beams for different power spectrum slopes revealed that non-Kolmogorov atmosphere can severely alter the initial spectral composition, leading to both blue and red shifts [36] (see Fig. 1).

b) turbulence in with presence of scatterers [48]

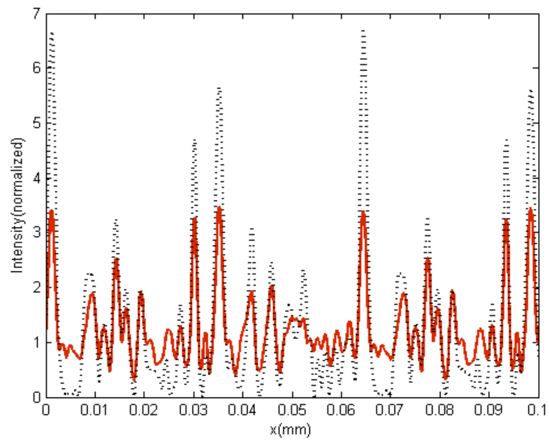

Fig. 2. The intensity of a plane wave scattered by particles and normalized by its value on the axis vs. radial distance from the optical axis: with turbulence (solid curve); without turbulence (dotted curve).

We have recently developed a theory which makes it possible to predict interaction of stochastic electromagnetic waves with turbulent medium containing particles with weak potentials [48]. Our new method is based on the idea that both propagation of a wave in a continuous medium and weak scattering can be formulated with the help of the angular spectrum representation of the waves. We have derived the following expression for the cross-spectral density function of the field after transmission through turbulent and particulate random medium:

$$W^{(s)}(\mathbf{r}_1,\mathbf{r}_2;\omega)=\left(\frac{k}{2\pi}\right)^2\iint\frac{1}{u_{1z}u_{2z}}\iint A^{(i)}(\mathbf{u}_1',\mathbf{u}_2';\omega)$$

$$\times\mathbf{C}_F\left[-\mathbf{K}_1,\mathbf{K}_2;\omega\right]d^2\mathbf{u}'_{1\perp}d^2\mathbf{u}'_{2\perp}\,\mathrm{e}^{ik(\mathbf{u}_2\cdot\mathbf{r}_2-\mathbf{u}_1\cdot\mathbf{r}_1)}$$

$$\times\exp\left[2E^{(1)}_{\mathbf{u}_1,\mathbf{u}_2}(\mathbf{r}_1,\mathbf{r}_2;\omega)+E^{(2)}_{\mathbf{u}_1,\mathbf{u}_2}(\mathbf{r}_1,\mathbf{r}_2;\omega)\right]d^2\mathbf{u}_{1\perp}d^2\mathbf{u}_{2\perp}\,. \quad (1)$$

Here $A^{(i)}$ is the angular correlation function of the incident wave $\mathbf{C}_F$ is the Fourier transform of the correlation function of the scattering medium. Finally, $E^{(1)}$, $E^{(2)}$ are the Rytov integrals which represent the effects of the turbulence. Thus the cross-spectral density function of the scattered field has been related to the correlation properties of the incident field, as well as with the statistics of turbulence and scattered collection. Figure 2 shows a simulation based on Eq. (1)

revealing that the effects of turbulence and of the scattering collection can compensate each other.

c) statistics of various beams in turbulence [7-8], [10], [14], [19], [23], [29], [42]

We have done several deep studies about evolution of various the second-order and the fourth-order statistical properties of optical beams. In [7-8] and [42] the scintillation index of J-Bessel, I-Bessel, cos-Gaussian and cosh-Gaussian was calculated for the atmospheric boundary layer based on a numerical technique, specifically developed for this purpose. We have shown the advantages of using these classes of beams for mitigation of scintillation, compared with typical lowest-order Gaussian beam. In [10] the propagation in the atmosphere of the degree of cross-polarization of a typical stochastic beam was investigated. A new mechanism of reduction of the scintillation index was introduced in [14] which is based on superposition of two orthogonally polarized modes. An important beam quality factor, known as M^2 factor, was evaluated in [19, 29] for an important classes of dark-hollow beams and electromagnetic Gaussian Schell-model beams, showing some advantages of using these beams instead of classic Gaussian modes. In [23] we have analyzed the beam wander of J-Bessel and I-Bessel beams in turbulence.

4. Systems operating in turbulent atmosphere

a) LIDARs [5], [11], [34]

On the basis of 4x4 tensor approach we have formulated a theory for predicting the second-order statistical properties of electromagnetic Gaussian Schell-model beams in LIDAR systems operating in the clear-air turbulent atmosphere and sensing targets with arbitrary roughness [5, 11]. In Fig. 3 we show a generic evolution of the intensity distribution and polarization ellipse as a beam goes through the LIDAR system. In [34] we have developed sensing techniques which utilize the degree of coherence and the orientation of the polarization ellipse of the beam.

5. Other topics:

Among other topics which were considered by our group are the analysis of pulsed fields [27], [37-38], canard explosion in semiconductor optical amplifier [46] and stochastic beam interaction with oceanic turbulence [39], [45].

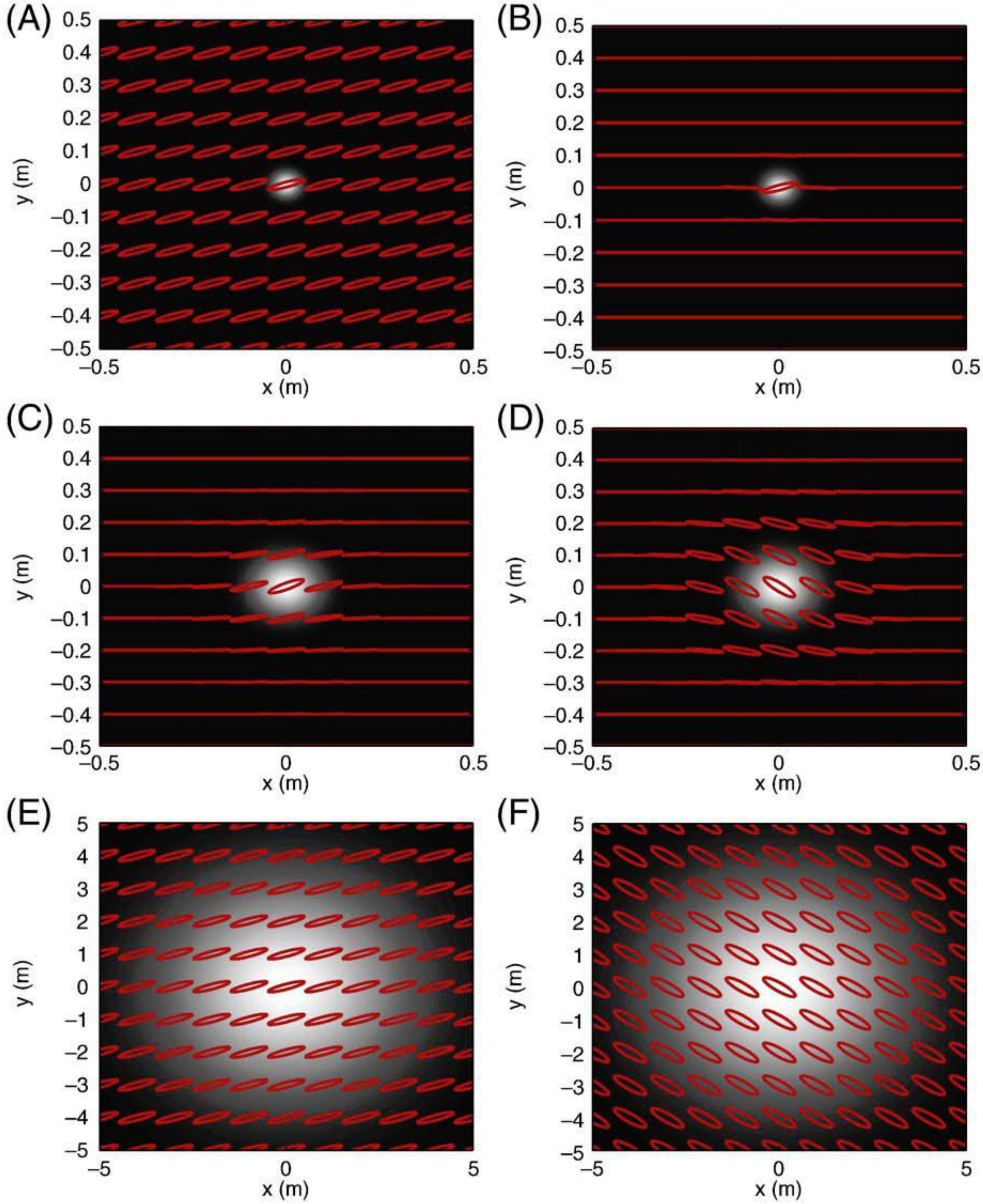

Fig. 3. Propagation of polarization ellipses through a LIDAR system in case of a uniformly polarized source (A), (C) and (E) and non-uniformly polarized (B), (D) and (F). Figures (A), (B) source plane; (C), (D) target plane; (E), (F) collecting lens plane.

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51. O. Korotkova, "Invariance in polarization properties of beams generated by quasi-homogeneous sources" (Opt. Lett., in press 2011).

Conference presentations

1. Photonics West, SPIE meeting (January 2008, San Jose, CA) Contributed talk: "Spectral changes in EM stochastic beams propagating in the atmosphere" Contributed poster: "The effect of a jet-stream and gravity waves on characteristics of a Gaussian beam propagating in upper layers of a turbulent atmosphere" Contributed poster: "Beam criteria for atmospheric propagation."
2. Seminar Series of the Department of Mathematics (February 2008, Orlando, FL) Invited talk: "Theory and applications of stochastic beams."
3. TCATS: AFOSR workshop (March 2008, Dayton, OH) Invited talk: "Mitigation of atmospheric effects by means of partial polarization."
4. EOS Annual Meeting (September 2008, Paris, France) Contributed talk: "Application of the SLMs for atmospheric propagation problems."
5. OSA Annual Meeting (October 2008, Rochester, NY) Contributed Talk: "Scattering of random fields from random collections of particles" (jointly with S. Sahin) Contributed Talk: "Application of spectral shifts for inverse scattering" (jointly with D. Zhao and E. Wolf).
6. Electromagnetics Workshop (January, 2009, San Antonio, TX) Invited Talk: "Active Laser Radar Systems with EM partially coherent beams"

7. Photonics West (January 2009, San Jose, CA) Contributed Talk: “Fluctuations in Stokes parameters of stochastic EM beams in turbulent atmosphere” (jointly with S. Sahin) Contributed Poster: “Cross-polarization of random beams on propagation in free space and in the atmosphere” (jointly with S. Sahin, G. Zhang, J. Pu) Contributed poster: “Speckle-field simulator characterization” (jointly with J. Cordray, E. Watson and I. Anisimov)
8. Department of Mathematics Seminar Series, US Navy Academy (Annapolis, MD, March 2009) Invited talk: “Atmospheric Applications of Random Electromagnetic fields”.
9. Defense and Security SPIE meeting (Orlando, FL, April 2009) Contributed talk: “Coherence and polarization properties of returns in active laser radar systems” (jointly with S. Sahin, Z. Tong).
10. “Partial EM coherence and 3D polarization” Workshop (Koli, Finland, May 2009) Invited talk: “Use of coherence and polarization of light in communications and remote sensing through atmospheric turbulence”
11. “Waves in Complex Media” workshop (University of Irvine, Yontville, CA, June 2009) Invited talk: “Propagation of stochastic electromagnetic fields in atmospheric turbulence with applications for free space optical communication systems and LIDARs”
12. Department of Physics Seminar Series (University Roma Tre, Rome, Italy, July 2009) Invited talk: “Statistical optics of natural environments”
13. Graduate Student Seminar of the Department of Physics (September 2009, Miami, FL) Talk: “Interaction of random EM fields with natural random media”.
14. OSA Annual Meeting (San Jose, CA, October, 2009) Invited talk: “Modulation of polarization properties of beams for LaserCom and LIDAR systems operating in random media”
15. AROSR Electromagnetics Workshop (San Antonio, TX, January, 2010), Invited talk: “Ghost imaging through turbulent atmosphere”.
16. SPIE symposium “Photonics West” (San Francisco, CA, January, 2010), Contributed poster: “Polarization changes in random electromagnetic beams propagating in the oceanic turbulence” (jointly with N. Farwell), Contributed talk: “Comparison of fractional powers of several classes of beams” (jointly with S. Sahin, R. Malek-Madani, Y. Cai), Contributed talk: “Spectral changes and spectral switches in stochastic EM beams in negative phase materials” (jointly with Z. Tong), Contributed talk: “Ghost imaging in turbulent atmosphere” (jointly with Y. Cai).
17. Undergraduate Research Atlantic Coast Conference "Meeting of the Minds" (Georgia Institute of Technology, Atlanta, GA, April 2010). Contributed poster: “Polarization and intensity correlations in stochastic electromagnetic beams upon interaction with devices of polarization optics” (jointly with Hilary Jacks).
18. Department of Technical Cybernetics, Samara State Aerospace University, Russia (May 2010). Invited talk: “Interaction of stochastic electromagnetic beams with natural media”.
19. Department of Physics, Soochow University, China (July 2010). Invited talk: “Interaction of stochastic electromagnetic beams with natural media”.
20. ONR workshop, Annapolis MD (July 2010). Invited paper: “Estimating intensity probability density function for maritime environment at United States Naval Academy” (jointly with S. Avramov-Zamurovic).
21. Department of Physics, Florida Atlantic University (October 2010). Invited talk: Random optical beams in random media”
22. OSA annual meeting, Rochester, NY (October 2010). Contributed paper: “Far-field analysis of Gaussian-Schell-model beams” (jointly with Z. Tong).

23. DEPS annual conference, Bethesda, MD (November 2010). Contributed paper: “Laser beam experiments in maritime environment” (jointly with S. Avramov-Zamurovic and R. Malek-Madani).
24. Southeast Conference for Undergraduate Women in Physics (January 2011). Contributed paper: “Fourth-order moments of the optical field produced upon scattering” (jointly with H. Jacks).
25. SPIE symposium “Photonics West” (San Francisco, CA, January, 2011), Contributed paper: “Hybrid technique for propagation and scattering from random medium containing random distribution of particles” (jointly with Z. Tong), Contributed paper: “Spectral, coherence, and polarization properties of beam-like optical fields propagating in non-Kolmogorov atmospheric turbulence” (jointly with E. Shchepakina), Contributed paper: “Probability density function of fluctuating intensity of laser beam propagating in marine atmospheric turbulence” (jointly with S. Avramov-Zamurovic and R. Malek-Madani).
26. PIERS symposium (Marrakesh, Morocco, March 2011) Contributed paper: “Propagation of Random Electromagnetic Beams in Non-Kolmogorov Atmospheric Turbulence” (jointly with E. Shchepakina).
27. SPIE Defense and Security Symposium (Orlando, FL, April 2011) Contributed poster: Far-field scattering of random electromagnetic fields from particulate media (jointly with Z. Tong); Contributed paper: Interaction of stochastic electromagnetic beams with human eye (jointly with S. Sahin); Contributed paper: “PDF computations for power-in-the-bucket measurements of an IR laser beam propagating in the maritime environment” (jointly with C. Nelson, R. Malek-Madani, S. Avramov-Zamurovic, R. Sova, F. Davidson).
28. International Conference “Differential Equations and Related Topics” dedicated to 110-th Anniversary of I. G. Petrovskii (Moscow, Russia, May-June, 2011) Contributed talk: “Control of the canard explosion in a semiconductor optical amplifier” (jointly with E. Shchepakina).
29. DEPS Beam Control Conference, (Orlando, FL, May 2011). Contributed talk: “Experimental study of the probability density function of the intensity of a turbulence-induced fluctuating laser beam” (jointly with R. Malek-Madani, S. Avramov-Zamurovic, J. Watkins, W. Peabody and A. Browning).
30. OSA Topical Meeting on FSO Communications (Toronto, Canada, July 2011). Invited talk: “Stochastic electromagnetic beams for sensing and free-space communications”.

Rewards received

1. X. Du, D. Zhao, O. Korotkova, “Changes in the statistical properties of stochastic anisotropic electromagnetic beams on propagation in the turbulent atmosphere”, Optics Express 2007, 15(25): 16909-16915 “After a comprehensive assessment of academic measurement indicators, this paper is entitled “Top 100 international scientific papers of most influence in China” hereby certified”. China Science & Technology Information Institute, 2009.

2. Scholarly and Creative Activities Award, College of Arts and Sciences, University of Miami, May 2010.